AN INVESTIGATION OF REINFORCED CONCRETE BEAMS FAILING IN SHEAR

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KEITH GEORGE EDWARD MOODY

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Introduction

The problems related to the strength and behaviour of reinforced concrete beams subject to shear and flexure have received considerable attention in the past. From many experimental investigations, qualitative and quantitative knowledge of an empirical nature was obtained, but there remained many unsolved problems, particularly with respect to the behaviour near the ultimate load of beams failing in shear.

The chief purpose of the work reported in this thesis was to determine (1) the behaviour and modes of failure of simple beams with and without web reinforcement, and (2) the behaviour and modes of failure of restrained beams with and without web reinforcement. Data for the study of these questions was obtained from tests of 138 simple and restrained beams, in which the influence of an extensive range of variables was investigated. Other information was obtained from a re-analysis of the results of tests of 120 beams reported by earlier investigators.

Tests Of Simple Beams

Tests of 42 simple beams, comprising three series, are reported in this thesis. All beams were of rectangular cross-section, and the following major variables were included:

(a) Size of beams: 7 in. by 12 in., 6 ft 3 in. long to 7 in. by 24 in., 10ft long

(b) Concrete strength: 850 psi to 5950 psi

(c) Amount of longitudinal reinforcement: 0.80 to 4.25 percent

(d) Shear span to depth ratio: 1.52 to 3.41

In addition, the effects of variations in the concrete mixtures was studied in one series, and the effect of the arrangement of longitudinal bars was studied in another. The third series included compression reinforcement and in two beams of the same series, vertical stirrups were provided.

All specimens were tested in static short-time tests. The load was applied in increments, and the midspan deflection and strains on the tensile reinforcement and compressive concrete were measured after each increment. The development of diagonal tension cracks and the mode of failure of the beams was observed visually.

All beams failed in shear. Immediately after the inception of loading, the beams behaved essentially in an elastic manner. At higher loads, diagonal tension cracks were initiated; the load at which this occurred was expressed empirically in terms of the nominal shearing stress.

In a number of beams, the load at which diagonal tension cracks formed was the maximum load sustained by the beam. In most cases however, further increases of load were possible, as a redistribution of internal stresses took place. Thereafter, the beams were maintained in equilibrium under the applied load, the normal and shear stresses in the compression zone of the beam, and the tensile force in the reinforcement.

The predominant mode of failure of simple beams was by destruction of the compression zone. The diagonal tension cracks penetrated further into the beams than would flexural cracks at the same load, and by restricting the area of the compression zone, reduced the strength of the beams. An analysis of the ultimate strength of beams failing in this manner was made in terms of the ultimate moment, and a good agreement resulted. The results of this analysis indicated that the effect of the shear force in weakening the compression zone was small indeed.

The scope of the data on simple beams was enhanced considerably by the use of the results of earlier investigations

by Richart and Jensen, Moretto, and Clark. The results of the latter investigations were also utilized to obtain expressions for the effects of vertical and inclined stirrups on the shear strength of simple beams.

Tests Of Restrained Beams

Tests of 96 restrained beams, divided into five series, are reported in this thesis. All beams were of rectangular cross-section except two, which were T-beams. The beams were supported at two points, and loaded at three or four points on the upper surface of the beam within the span and on projecting cantilevers, so as to apply various ratios of positive and negative moments to the beams.

The following major variables were included in the tests:

(a) Cross-section of beams: 7 in. by 15 in. and 7 in. by 24 in.

(b) Length of beams: 15 ft 4 in.

(c) Concrete strength: 2300 psi to 6020 psi

(d) Amount of longitudinal reinforcement: 0.54 to 4.76 percent

(e) Shear span to depth ratios: 1.53 to 4.00

(f) Ratios of maximum negative to maximum positive moments: 1 and 2

(g) Amount of vertical or inclined stirrups: 0.52 to 2.14 percent

The longitudinal reinforcement was continuous throughout the length of the majority of beams. However, one series of beams was included to investigate the effects of cutting off the longitudinal reinforcement in accordance with the provisions of the ACI Code 318-51.

The method of testing was identical with that used for the tests of simple beams. Immediately after the inception of

loading, the beams behaved essentially in an elastic manner. At higher loads, diagonal tension cracks were initiated in the vicinity of the section of maximum moment, in the region of maximum shear. The nominal shearing stress at which diagonal tension cracks formed was expressed by an empirical equation obtained from the test data.

For the restrained beams with continuous longitudinal reinforcement, the ultimate loads were from 1.08 to 3.20 times greater than those at which diagonal tension cracks formed. The action of the beams was radically different from that which would be expected from the ordinary theory of flexure for homogeneous beams.

This behaviour was marked by the occurrence of redistribution of internal stresses in two distinct stages. The first stage of redistribution accompanied the complete development of the initial diagonal tension cracks. The second stage occurred following the development of a second major diagonal tension crack, with a direction more or less parallel to the initial crack, in the region of maximum shear. The load at which the second diagonal tension crack formed was also expressed by an empirical equation in terms of the nominal shearing stress.

Some beams failed after only the first stage of redistribution, but in most cases the second stage occurred before failure. In all beams, failure was due to the destruction of the compression zone at the section of greatest moment in the region of maximum shear.

No well defined differences appeared to exist between the beams which failed in each of these two ways, and it was found by analysis that for all practical purposes, it could be assumed that both the first and second stages of redistribution of internal stresses occurred in all beams before failure. An analysis of the ultimate strength of restrained beams failing in shear was made in terms of ultimate moment, and a good agreement resulted. The results of this analysis indicated that only in the case of very deep beams does the presence of

shear stresses affect the strength of the compression zone significantly.

The behaviour described above applied only to beams in which the reinforcement was continuous. In beams in which the longitudinal reinforcement was cut off in accordance with the provisions of the ACI Code 318-51, the initiation of diagonal tension cracking was followed almost immediately by failure, the beams breaking into two completely separate parts. It is believed that failures of this type should be prevented entirely by requirements regarding the arrangement of the longitudinal reinforcement.

Effects Of Web Reinforcement

Before the formation of diagonal tension cracks, the effect of web reinforcement on the behavior of the beams was negligible. The load at which diagonal tension cracks formed was not significantly different from that for beams without web reinforcement.

After initial diagonal tension cracking, the action of the stirrups was one of restricting the opening of the dagonal tension cracks. However, near ultimate, phenomena were observed which indicated that redistribution of internal stresses had occurred.

Observations of strains on the stirrups indicated that for beams with vertical stirrups, only in those with the lower percentages were all stirrups yielding before failure. On the other hand, in beams with inclined stirrups, all stirrups were yielding before failure, regardless of the amount provided.

Failure of beams with web reinforcement was due to destruction of the compression zones. The web reinforcement appeared to have two strengthening effects:

1. To increase the shearing resistance of the beam in the region of maximum shear by the vertical component of the tension in the stirrups at failure.

2. To delay the concentration of deformation in the concrete in the compression zones where failure occurs, by restricting the opening of diagonal tension cracks in the region of maximum shear.

The strength of both simple and restrained beams with vertical stirrups was expressed as the sum of the moment resistances of the compression zone of the beam at the critical section, and that due to the vertical stirrups about this section. The first part of this equation is the strength of an identical beam without stirrups, and the second part was expressed by an empirical equation derived from test data. Good agreement was obtained with the test results.

Because of the lack of data, no such expressions could be derived for inclined stirrups, although it is believed that similar equations would be possible.

Concluding Remarks

In this chapter, the relationship between the modes of failure of reinforced concrete beams is discussed. It is shown that shear failure of beams by destruction of the compression zone is a phenomenon similar to flexural compression failures. As in the case of compression failures, under some circumstances a beam may fail simultaneously in shear and by yielding of the tensile reinforcement, that is, points of balanced failure exist. The significance of the diagonal tension cracking load is also discussed; it is shown that, depending on the design of the beam and the method of loading, the maximum load which a beam may sustain will be determined (a) when diagonal tension cracks form or (b) when the compression zone is destroyed at a load somewhat greater than that at which diagonal tension cracks form. Furthermore, it is believed that these cracks will always form at a load less than that at which compression failures would occur, in which case compression failures would not be possible in beams without web reinforcement.

The question of the design of beams is also considered.

The undesirable nature of shear failures as compared with tension failures is pointed out, and because of this fact, it is believed that beams should be designed in such a manner that shear failures are prevented entirely. This may be accomplished by limiting the allowable "tension reinforcement index" to a value less than that for which balanced shear and tension failures would occur. A similar requirement may be used for the design of web reinforcement.

VITA

Keith G. E. Moody was born in Geelong, Victoria, Australia on September 10, 1925. He attended state schools and the Gordon Institute of Technology, Geelong, from which he graduated in 1942. In January 1943, he received an appointment with the Country Roads Board of Victoria, and was employed for the following three years on construction projects in the State of Victoria, and the Northern Territory. In 1946, he entered the Universty of Melbourne, from which he graduated in February 1949 with the degree of Bachelor of Civil Engineering with First Class Honors. He was appointed a research assistant in the Department of Civil Engineering, and worked under the direction of Dr. J. A. L. Matheson, Professor of Civil Engineering, on an investigation of the inelastic behavior of steel columns. The results of this investigation were presented in a thesis entitled "The Behavior of Steel Columns Loaded by Constant End Moments," for which he was awarded the degree of Master of Engineering Science with First Class Honors, in December 1950.

He was appointed an Assistant Engineer with the Country Roads Board of Victoria in 1950, and worked on road and bridge construction projects until August 1951. In March 1951, he was appointed as a Dominion Service Fellow of the Commonwealth Fund (New York). Under the terms of this Fellowship, he has pursued graduate studies at the University of Illinois from September 1951 until the present time.